TÜRKİYE CUMHURİYETİ
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL
MECHANICAL ENGINEERING DEPARTMENT

THERMODYNAMIC ANALYSIS OF A DIRECT-FIRED BIOMASS POWER PLANT

BERİL BÜŞRA YAŞAR TOPRAK

M.Sc.

ADANA 2025

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THESIS ADVISOR
PROF. DR. İBRAHİM HALİL YILMAZ

ADANA, 2025

DECLARATION OF CONFORMITY

In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

10/02/2025

[Signature]

Beril Büşra YAŞAR TOPRAK

ÖZET

DOĞRUDAN YAKMALI BİR BİYOKÜTLE GÜÇ SANTRALİNİN TERMODİNAMİK ANALİZİ

Beril Büşra YAŞAR TOPRAK
Yüksek Lisans, Makine Mühendisliği Anabilim Dalı
Danışman: Prof. Dr. İbrahim Halil YILMAZ
Şubat 2025, 41 sayfa

Bu tez, 2014 yılından bu yana buhar çevrimine dayalı olarak faaliyette olan, Adana ilinde faaliyet gösteren 1,76 MWe'lik doğrudan yakmalı biyokütle enerji santralinin termodinamik analizini sunmaktadır. Santral, fabrikanın enerji ihtiyacının bir kısmını karşılamak için tarım ve orman atıklarını kullanmaktadır. Çalışma, operasyonel verilerin toplanmasıyla başlayan ve ardından temel bileşenler için termodinamik dengeler izleyen yapılandırılmış bir metodolojiyi takip etmektedir. Enerji ve ekserji dengeleri, sistem performansını kapsamlı bir şekilde değerlendirmek için uygulanmaktadır. Bu hesaplamalar, mühendislik ve termodinamik modelleme için ticari bir yazılım olan Engineering Equation Solver kullanılarak uygulanmaktadır. Daha iyi sistem verimliliği için her sistem bileşeni için parametrik çalışmalar yürütülmektedir. Sonuçlar, bileşene özgü verimsizlikler hakkında fikir vererek, sistem optimizasyonu ve verimlilik iyileştirmeleri için rehberlik sunmaktadır. Santralin birinci yasa verimliliği, literatür verileriyle tutarlı olarak %16,5 olarak hesaplanmıştır. Özellikle ısı değiştiricilerin giriş basınçlarının ve sıcaklıklarının optimize edilmesi, santral performansını daha da artıracaktır. Bu araştırma, iyileştirme için kritik alanları belirleyerek, Türkiye'de biyokütle bazlı güç üretiminin sürdürülebilir bir şekilde işletilmesine ve daha geniş çapta benimsenmesine katkıda bulunmaktadır.

Anahtar Kelimeler: Tarımsal artıklar, Biyokütle güç santrali, Doğrudan yakma, Proses iyileştirme, Termodinamik analiz

ABSTRACT

THERMODYNAMIC ANALYSIS OF A DIRECT-FIRED BIOMASS POWER PLANT

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M.Sc., Department of Mechanical Engineering

Supervisor: Prof. Dr. İbrahim Halil YILMAZ
February 2025, 41 pages

This thesis presents a thermodynamic analysis of a 1.76-MWe direct-fired biomass power plant operating in Adana, Turkiye, which has been in operation since 2014 based on a steam cycle. The plant utilizes agricultural and forest residues to meet a portion of the factory's energy needs. The study follows a structured methodology, beginning with the collection of operational data, followed by thermodynamic balances for key components. Energy and exergy balances are applied to assess system performance comprehensively. These calculations are implemented using Engineering Equation Solver, a commercial software for engineering and thermodynamic modeling. Parametric studies for each system component are conducted for better system efficiency. The results provide insights into component-specific inefficiencies, offering guidance for system optimization and efficiency improvements. The first-law efficiency of the plant is calculated to be 16.5%, which is consistent with the literature data. Optimizing inlet pressures and temperatures of particularly the heat exchangers would enhance the plant performance higher. By identifying critical areas for enhancement, this research contributes to the sustainable operation and broader adoption of biomass-based power generation in Turkiye.

Keywords: Agro residues, Biomass power plant, Direct-fired biomass, Process intensification, Thermodynamic analysis

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor, Prof. Dr. İbrahim Halil YILMAZ, for their invaluable guidance, expertise, and unwavering support throughout this journey. His insights and encouragement have been fundamental to the development of this research.

I am also grateful to the Committee Members for their constructive feedback and for reviewing my work. Their perspectives have greatly enhanced the quality of this thesis.

I would like to express my deepest gratitude to all those who have supported me throughout the completion of this thesis. This thesis would not have been possible without the support of Pakmil Energy Plant, and I am deeply grateful to the company.

I extend my appreciation to my family for their continuous support and understanding during my studies. Their love and patience have been a constant source of strength.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACC	: Air-cooled condenser
BPP	: Biomass Power Plant
C	: Condenser
CHP	: Combined Heat and Power
EES	: Engineering Equation Solver
ESP	: Electrostatic Precipitation
HEX	: Heat Exchanger
HHV	: Higher Heating Value
LHV	: Lower Heating Value
MSW	: Municipal Solid Waste
ORC	: Organic Rankine Cycle
P	: Pump
T	: Turbine

LIST OF SYMBOLS

h	: Enthalpy, kJ/kg°C
LHV	: Lower heat value, kJ/kg
$\dot{m}$	: Mass flow rate, ton/h
s	: Entropy, kJ/kg°C
$\dot{Q}$	: Heat transfer rate, kW
T	: Temperature, °C
T_0	: Dead state temperature, °C
$\dot{W}$	: Power, kW
$\dot{X}$	: Exergy rate, kW
ε	: Exergy efficiency
η	: Energy efficiency
η_g	: Generator efficiency
η_t	: Thermal efficiency
ψ	: Specific flow exergy, kJ/kg

1. INTRODUCTION

With its extensive biomass activities, Turkiye produces large amounts of field, garden, vegetable crop, and forestry residuals. Major regions like Central Anatolia, the Aegean, and the Marmara regions generate a considerable share of these residues. Residuals are often burned directly in small-scale boilers or furnaces for heating purposes. However, this practice is mostly limited to rural and agricultural areas. Some direct combustion biomass power plants (BPPs) utilize agricultural residuals as feedstock to generate electricity. Direct combustion BPPs in Turkiye have been increasingly contributing to the country's renewable energy landscape. By the end of 2021, there were 174 licensed BPPs in Turkiye where the total installed capacity of BPPs was 2.3 GWe, accounting for 2.3% of the nation's total electricity generation (Enerji Atlası, 2025).

Open field burning of residuals, still common in some regions, causes air pollution and greenhouse emissions, negatively impacting the environment and public health. Collecting, transporting, and storing residuals efficiently is a major challenge. Residues are often scattered and bulky, making logistics expensive. Most plants designed for direct combustion in Turkiye are not optimized for biomass residuals, which have varying moisture content and calorific values. Biomass feedstock availability can be inconsistent due to seasonal variations. This affects the reliability of power generation, as the biomass supply might not be steady year-round. The quality of biomass materials can vary significantly. Biomass should be uniform in terms of moisture content and calorific value, but in practice, there may be challenges in maintaining consistency. High moisture content can reduce efficiency, and the variety of feedstock can make it harder to achieve optimal combustion conditions. The transportation and storage of biomass can be costly and complicated, especially when feedstock is sourced from scattered areas. Ensuring efficient logistics to minimize costs is a challenge in Turkiye.

The capital required to build BPPs is high, and while Turkiye has support mechanisms like feed-in tariffs (FiTs), the overall financial attractiveness can still be hindered by uncertain market conditions and high financing costs. Changes in regulations, subsidies, or FiTs can create uncertainty for investors and operators. If the government changes the terms of support or introduces new environmental regulations, it can significantly impact the viability of biomass plants. While biomass can be a relatively cost-effective energy source in some cases, the operational costs (including procurement of feedstock and maintenance of equipment) can be unpredictable, especially if feedstock prices rise or become volatile.

The waste management hierarchy is a method used to rank the most and least advantageous actions in terms of resource and energy consumption as well as environmental protection. The hierarchy determines preferred program priorities according to sustainability. Waste management requires an integrated approach to be sustainable; technological end-of-pipe solutions alone will not suffice. The waste management hierarchy is typically shown diagrammatically as a pyramid as seen in Fig. 1.1. The waste hierarchy seeks to produce the least amount of waste while maximizing the useful benefits from items.

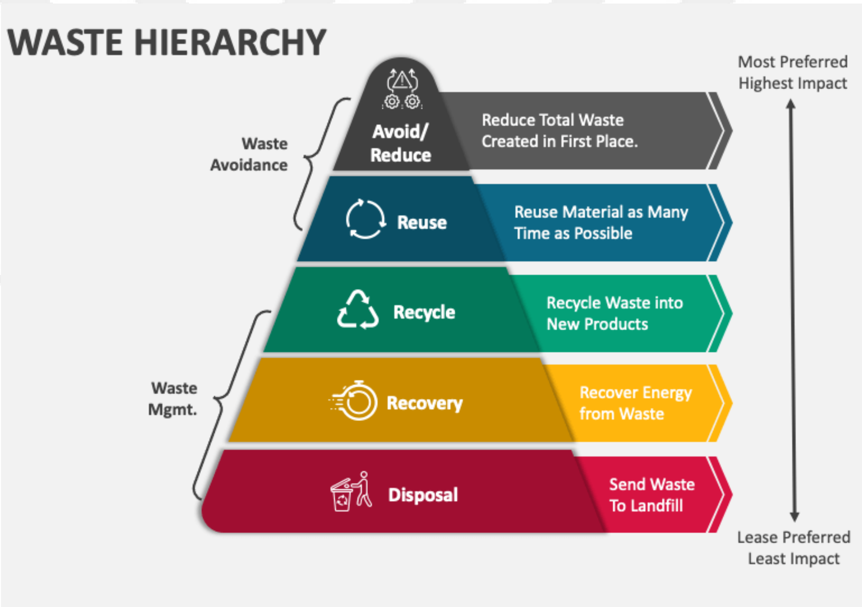

Fig. 1.1. Waste management hierarchy.

Studies suggest that the energy potential from Turkiye's biomass residues could significantly contribute to the country's renewable energy targets. The residues could be used for heat and electricity generation. Proper utilization of residuals in energy production can reduce environmental issues like soil erosion and air pollution. Increased subsidies, tax exemptions, and grants for bioenergy projects could encourage the use of residuals in biomass power generation.

Direct combustion of residuals in Turkiye has vast untapped potential to contribute to renewable energy production. BPPs are built to produce electricity by converting the heat energy generated by the combustion of biomass waste into high-pressure superheated steam. In BPPs, facility design and manufacturing can be done according to both fluidized bed and moving grate technology. Overcoming logistical and technological challenges through strategic investments, policy support, and innovation could transform this sector into a significant player in the country's renewable energy portfolio.

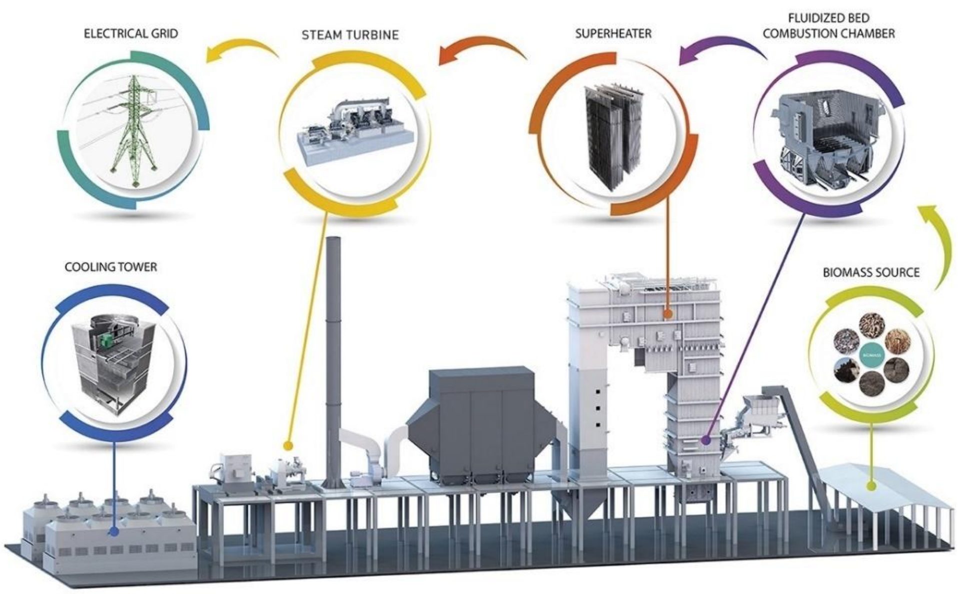

Fig. 1.2. Bioenergy to electricity (Mimsan, 2025).

The direct combustion of biomass residuals for power production in Turkiye represents a promising but underutilized sector within the country's renewable energy landscape. Biomass residuals, such as crop stalks, husks, shells, and pruning waste, are abundant and have significant potential as feedstock for BPPs. While Turkiye has vast potential for energy generation through the direct combustion of residuals, realizing this potential requires overcoming logistical, technological, and policy challenges. Although some biomass power plants in Turkiye use biomass residuals as feedstock, the scale remains small compared to the potential. The Pakmil Energy Plant is an example of a facility utilizing such residuals (e.g., cotton and corn stalks, and forestry disposals) for its operations and the first direct-fired BPP installed in Turkiye (see Fig. 1.3).

Fig. 1.3. A view from the Pakmil Energy Plant.

Thermodynamic analyses of direct combustion of residuals are crucial for optimizing energy conversion efficiency and understanding the environmental impacts of biomass utilization. Energy and exergy analyses of direct-fired BPPs provide critical insights into the performance, efficiency, and sustainability of the plant's operations.

Energy analysis focuses on energy conservation within a system, ensuring that the plant is operating efficiently by tracking how energy is converted and distributed throughout the system. It helps to assess the overall efficiency of the plant in converting the chemical energy of biomass into useful electricity or heat. By tracking energy flows, it helps identify where energy losses occur (e.g., in combustion, heat exchange, or power generation).

Exergy analysis is a more detailed evaluation that considers both the quantity and quality of energy within the system. Exergy provides a measure of how far the energy in the system is from being able to perform useful work. This is important because not all forms of energy are equally capable of being converted into work. It helps identify locations in the system where energy degradation (irreversibility) is occurring, such as in the combustion process, heat exchange, or during electricity generation. This allows for targeted improvements to reduce energy losses. By analyzing exergy destruction, plant operators can pinpoint inefficiencies and improve system design or operational strategies to minimize waste and enhance performance.

Energy and exergy analyses can help identify areas for improvement, leading to better plant efficiency and reduced operational costs. Understanding energy flows and quality through exergy analysis can help reduce fuel consumption, lowering operational costs. By assessing both energy efficiency and the quality of energy available for work, a BPP can be better optimized for maximum output with minimal waste.

1.1. Motivation

The motivation for thermodynamic analysis of direct-fired BPP stems from several key factors related to optimizing performance, improving efficiency, and reducing environmental impacts. As the first direct-fired BPP installed in Turkiye, the Pakmil Energy Plant has faced some obstacles in the boiler during its operations and experienced inefficient practices. Through these analyses, inefficiencies can be identified for specific parts of the plant (e.g., turbine, pumps, or heat exchangers) where improvements can be made. Thermodynamic analyses are crucial tools for enhancing the efficiency, sustainability, and economic viability of direct-fired BPPs, contributing to their broader acceptance by investors and adoption as a cleaner energy alternative for Turkiye.

1.2. Aim of The Thesis

The proposed thesis aims to conduct a thermodynamic analysis for an operating 1.76-MWe direct-fired BPP using agricultural residues. Parameters of system components that significantly influence power production are investigated. This thesis proposes a thermodynamic model for determining the critical parameters of the plant and its losses or components to be improved thermodynamically. Thermodynamic analyses are conducted based on performance parameters such as energetic efficiency, exergetic efficiency, and component exergy destruction.

2. LITERATURE REVIEW

A significant portion of the studies have been dedicated to evaluating the potential of agricultural biomass for energy production. This includes its use in bioenergy applications such as biogas production, biofuels, and direct combustion for heat and power generation. Many studies have analyzed how much energy could be generated from the available agricultural biomass, considering factors like crop types, harvest yields, and collection practices.

The researchers have discussed the challenges of fully exploiting agricultural biomass resources in Turkiye. These might include technical difficulties related to biomass collection and processing, lack of infrastructure for biomass energy production, and financial barriers such as high initial investment costs for setting up biomass conversion facilities.

Demirbas (2008) discussed the potential of various agricultural residues in Turkiye, such as grain dust, crop residues, and fruit tree residues, as sources of biomass energy. Among these, fuelwood stands out as a significant source, contributing 21% of Turkiye’s total energy production due to its high availability and simple conversion techniques. Saka and Yılmaz (2017) evaluated the agricultural biomass potential in Turkiye, focusing on the availability of biomass resources derived from the country’s agricultural activities and how these resources can be utilized for sustainable energy production and other purposes. Given Turkiye’s strong agricultural sector, the paper explored both the types of agricultural biomass available and their potential for contributing to the country’s energy needs. Yılmaz and Saka (2018) also focused on evaluating the status and potential of biomass resources in the Southeastern Anatolia Region of Turkiye, exploring how these resources can be exploited for sustainable energy production and other uses. The research examined the types of biomasses available, their current exploitation levels, and the region’s potential to expand biomass utilization to contribute to both energy needs and environmental sustainability. Saka et al. (2018) presented a detailed evaluation of Turkiye’s animal biomass energy potential, based on the country’s livestock. The research classified animal biomass into three major groups: bovine, small ruminants, and poultry, and then explored the potential of utilizing animal biomass for energy production from methane through anaerobic digestion. The authors analyzed the energy potential of each species by looking at waste production and energy output across different animal groups, offering a countrywide perspective on animal biomass use in Turkiye. According to the 2016 data, Turkiye's animal biomass could produce 1.36 million tons of oil-equivalent energy, significantly contributing to the country's energy mix.

Social factors, such as the need for farmer education and awareness of biomass opportunities, were not sufficiently considered in the literature. There is insufficient public awareness about the benefits of biomass energy. Some segments of the population may not understand the potential of biomass to reduce reliance on fossil fuels. In the Turkish context, Demir (2019) examined the waste management strategy in Adana under the Zero Waste Project and evaluated its implementation studies. Yılmaz and Abdulvahitoğlu (2019) evaluated various strategies for managing municipal solid waste (MSW) in Turkiye, focusing on how different approaches could contribute to energy recovery, carbon mitigation, and financial sustainability. Given Turkiye's increasing urbanization and waste generation, the study aimed to provide insights into how waste management systems can be optimized to address both environmental and economic challenges. Bilgili (2020) investigated the biomass potential for electricity energy substitution in Adana province using 2019 data from various governmental sources and previous research. He examined both plant and animal-originated biomass, revealing that Adana can produce 5% of Turkiye's plant residues and 1% of its animal residues, with a total annual biomass potential of about 23.56 PJ. This biomass potential could meet 34% of the province's energy demand, leading to a 95% reduction in CO_2 emissions compared to current energy consumption. Bilgili (2022) examined the potential for biomass-based electricity generation in Turkiye's Mediterranean Region, aligning with the country's goal of generating 30% of its total electricity from renewable sources by 2023. Using data from the Ministry of Energy and Natural Resources, Ministry of Agriculture and Forestry, Turkish Statistical Institute, and previous literature, the study analyzed the technical potential of plant and animal-originated biomass. It is estimated that these residues could meet 6.9% of the region's energy demand, or approximately 8.3 PJ/year. The use of biomass for electricity generation could reduce CO_2 emissions by 2.64 million tons annually. Additionally, 1.18 million tons of biofertilizer could be produced from biogas production. Tanrıverdi (2022) analyzed the potential of agricultural residues in Adana and suggested a possible biomass plant that can be built in Adana. He conducted a survey with 205 farmers in Adana's districts to observe the level of awareness about stubble fires. 88.3% of the farmers considered the stubble-burning process harmful and 55.1% of them declared that they do not have knowledge about biomass energy.

46.8% of the participants stated that they could keep agricultural residues for biomass energy applications. Pesen et al. (2023) investigated the most viable methods of processing biological waste in Adana, from energetic, environmental, and economic perspectives. The study showed that syngas (59% of bioenergy) and biogas (41%) can collectively generate 950,000 MWh of electricity from bioenergy. Of this, 560,000 MWh comes from syngas. This could meet 13.3% of Adana's electricity demand based on 2020 consumption. Substituting grid electricity with renewable energy from organic waste could reduce greenhouse gas emissions by 464,000 tons, and preventing organic waste decay could further cut 391,000 tons of emissions.

Dağtekin et al. (2019) assessed the biogas energy potential of broiler poultry manure in Adana and Mersin provinces, intending to generate sustainable energy solutions on a local scale. The study concluded that there is significant potential for biogas plants in these districts, which could provide electricity to support poultry house operations, such as powering electric motors, lighting, heating, water systems, and feed distribution. Caliskan and Ozdil (2021) analyzed Turkiye's biogas potential from animal manure between 2007 and 2019, highlighting regional variations, energy potential, and economic feasibility. The study estimated that biogas could supply 7.99% of Turkiye's electricity consumption during the analyzed period and suggested a discounted payback period of 10 years for a biogas facility. Ozdil and Caliskan (2022) also evaluated Turkiye's biomass potential from crops and its feasibility for electricity generation between 2008 and 2018. The total agricultural crop production was 771,354 kt, with 599,166 kt from arable field crops and 172,188 kt from horticultural crops. The theoretical biomass potential was estimated at 522,875 kt and 51,359 kt dry mass, respectively. The Central Anatolia and Mediterranean regions had the highest biomass potential. Electricity consumption during this period was $2{,}726\times10^9$ kWh, while the potential electricity generation from biomass was about 994×10^9 kWh, covering 36% of Turkiye's energy needs. Can (2021) examined the potential of animal manure from cattle and poultry in Adana for biogas production and energy generation. The study estimated the amount of electrical energy from cattle waste (342.32 MWhe/yr) and poultry waste (172.06 MWhe/yr) that could be generated by converting the manure into biogas.

The energy and exergy analyses of direct-fired BPPs have been the subject of various literature studies. These studies focus on assessing the efficiency, sustainability, and optimization of BPP systems. Energy analysis studies generally focus on evaluating the conversion of biomass fuel into usable energy (electricity or heat). Several studies have reported the thermal efficiency of direct-fired BPPs, typically ranging from 20% to 30%. This efficiency can vary depending on factors such as the type of biomass, combustion technology (e.g., grate firing, fluidized bed combustion), and the design of the plant. Research has focused on the energy content of different biomass fuels (e.g., wood chips, agricultural residues, MSW) and how these affect the plant's energy efficiency. Channiwala and Parikh (2002) studied the energy content of various biomass fuels and their impact on combustion efficiency in direct-fired power plants. Soltani et al. (2013) presented an advanced exergy analysis of an externally-fired combined-cycle power plant integrated with biomass gasification. The analysis identified the potential for improving the overall system by examining the interactions between its components. The study demonstrated that efforts to improve cycle performance should focus on the heat exchanger rather than the combustion chamber or gasifier, despite their higher exergy destructions. Malleki and Fatehi (2014) explored the potential of date palm trees producing about 40 kg of burnable waste annually. A sample power plant was designed using a steam Rankine cycle for electricity generation and thermal desalination for producing distilled water. Azami et al. (2018) presented a thermodynamic analysis of a municipal solid waste-to-energy boiler, focusing on energy and exergy balance equations across the entire system and its components. The energy and exergy analysis showed that the furnace was the primary source of exergy destruction. The overall energetic efficiency of the boiler was found to be 78.7%, while the exergetic efficiency was 16.0%. Braimakis et al. (2020) explores the performance of biomass-based combined heat and power (CHP) plants, particularly those using ultra-supercritical designs with steam temperatures of 600 °C, to meet heat demands in aluminum and pulp/paper industries while also providing district heating and cooling. In electricity-only modes, the aluminum and pulp/paper plants achieved electric and exergetic efficiencies of 43.45%/44.22% and 38.93%/39.62%, respectively. The exergy destruction occured during combustion (67–70%) and steam generation (13–16%). Yan et al. (2020) proposed a chemical looping oxy-fired biomass power plant with carbon capture and sequestration to address the low efficiency and uncertain life cycle CO_2 emissions of conventional biomass direct-fired plants. The new system was modeled and compared with a traditional air-fired BPP in terms of thermodynamics and economics. Sikarwar et al. (2020) proposed a novel configuration of a chemical looping combustion-based biomass power plant integrated with an organic Rankine cycle (ORC). The study investigated the effects of key design parameters, including the oxygen carrier-to-biomass ratio, operating pressure of air/fuel reactors, and the air reactor operating temperature, to enhance energy and exergy efficiencies.

Many studies utilize energy flow diagrams to analyze energy distribution across different stages, such as combustion, heat recovery, power generation, and losses. These diagrams help identify where energy losses occur and suggest potential improvements. Exergy analysis provides insights into optimizing the plant layout and operational parameters, such as improving heat recovery, optimizing combustion conditions, and using more efficient power generation technologies. Some studies have suggested the integration of CHP systems to utilize low-grade heat more effectively. Costa et al. (2019) analyzed mass, energy, and exergy flows in 50 MWth BPP using bubbling fluidized bed combustion. Focused on eucalyptus residual biomass in Portugal's pulp and paper industry. The findings highlighted that the highest exergy destruction occurs during combustion, while insulation minimizes energy losses. The main efficiency improvement opportunity lies in reducing the biomass moisture content.

Some studies have integrated both energy and exergy analyses to provide a comprehensive evaluation of BPPs. These integrated analyses are useful for better understanding of system performance and optimization opportunities. These studies often conclude that although energy efficiency can be improved by better fuel management and improved equipment, exergy analysis helps identify more fundamental system inefficiencies that require design modifications. Kaushik et al. (2011) discussed the growing global demand for power and the limitations of traditional power plant performance evaluations based solely on the first law of thermodynamics, which overlooks the quality of energy. The study compared the energy and exergy analyses of thermal power plants fueled by coal and gas and offered a comprehensive review of various studies on thermal power plants conducted over the years, highlighting areas for further research and providing recommendations for improving existing thermal power plants. Saidur et al. (2012) reviewed exergy analysis as a method for selecting the most efficient biomass as a renewable energy source. They examined different biomass types, including woody, herbaceous, agricultural, aquatic, contaminated, and industrial biomass. Various thermochemical processes were analyzed to assess their efficiency in converting biomass into energy. The study highlighted biomass and biofuels as environmentally friendly alternatives to fossil fuels, emphasizing their energy potential. Datta et al. (2010) analyzed the thermal performance and sizing of decentralized biomass-based power generation using an externally fired gas turbine across different cycle pressure ratios, turbine inlet temperatures, and heat exchanger cold end temperature differences. The study evaluated a 100 kW externally fired gas turbine plant to identify a balanced trade-off for performance optimization. Al-Sulaiman et al. (2012) presented energy and exergy analyses of a biomass trigeneration system using an ORC. Four cases were considered: electrical power, cooling cogeneration, heating cogeneration, and trigeneration. The study highlighted a significant performance improvement when trigeneration was employed compared to only electrical power production, with fuel utilization efficiency increasing from 12% for electrical power to 88% for trigeneration. Additionally, the maximum exergy efficiency of the ORC was 13%, which rised to 28% with trigeneration. The biomass burner and ORC evaporator were identified as the main sources of exergy destruction, with the biomass burner contributing 55% and the ORC evaporator 38% of the total exergy destruction. Mehmood et al. (2015) presented an exergy analysis of a biomass co-firing-based power generation system, examining the performance of a typical pulverized coal-fired steam cycle system using four biomass fuels (chicken litter, refuse derived fuel, rice husk, and sawdust) and two coals (bituminous coal and lignite). The study investigated the effect of biomass co-firing on exergy flows, losses, and efficiencies of both the boiler and the overall plant under different co-firing conditions. The results showed that as the biomass content in the fuel blend increases, the exergy efficiencies of both the boiler and the plant decrease. Sawdust blends leaded to the greatest decrease in efficiency, while chicken litter blends caused the least decline. Li et al. (2015) presented a theoretical framework for performing exergy analysis and advanced exergy analysis of a real biomass boiler. These analyses aimed to diagnose inefficiencies, optimize performance, and aid in the design of new biomass boilers. Conventional exergy analysis is used to identify sources of inefficiency and irreversibility, while advanced exergy analysis provides insights into avoidable exergy destruction and the potential for fuel savings in each component and the overall system. Ozdil and Atakan (2016) conducted exergy and exergoeconomic analyses of a biogas engine-powered electricity production system in a wastewater treatment plant in Adana, Turkiye. Exergy analysis revealed that the gas engine had the highest exergy destruction, followed by the exhaust gas heat exchanger (HEX) and lubrication oil HEX. The second-law efficiencies of system components ranged from 6.49% (pump) to 78.43% (turbine). Exergoeconomic analysis estimated the total system cost at 28.64

US$/h, with unit exergy costs of 4.88 US$/GJ for fuel and 11.32 US$/GJ for electricity production. Cavalcanti et al. (2019) evaluated the potential of eucalyptus biomass for thermal energy production in Brazil, focusing on its contribution to energy transition strategies. The study used exergy and exergoenvironmental analyses, based on the Specific Exergy Costing (SPECO) approach, for a steam power plant fueled by eucalyptus biomass. The findings revealed that components with high exergy destruction, such as feed water and pumps, have the worst environmental performance. The environmental impact rate per exergy unit of electricity was 7715 mPt/GJ. A sensitivity analysis showed that increasing boiler efficiency improves overall efficiency, reduces specific environmental impact, and decreases global exergy destruction. Al Asfar et al. (2020) conducted a thermodynamic analysis and environmental impact assessment of a lab-scale biomass-fired open-cycle power plant. The performance of the plant, including combustion and power generation efficiencies, was evaluated using the first and second laws of thermodynamics. The plant's energy and exergy efficiencies were found to be 12% and 16.4%, respectively. The primary source of irreversibility and energy loss in the plant was the heat addition process in the burner, due to non-adiabatic heat transfer in the un-insulated burner. Manić et al. (2021) revealed the impact of operational parameters such as biomass particle size, combustion temperature, and steam cycle efficiency on the overall performance of a BPP using wood pellets. Silva et al. (2016) presented an energy and exergy analysis of a BPP, identifying key areas of inefficiency and potential improvements. The plant was operated at different loads and the overall efficiency was calculated to be ~26%. The analysis is based on operational data and provides insights into optimizing plant performance. Eboh et al. (2017) overviewed the importance of exergy analysis in evaluating and improving the efficiency of thermal power plants. They highlighted the limitations of traditional energy analysis and positioned exergy analysis as a superior method due to its ability to account for system irreversibilities. Pan et al. (2020) presented a design to enhance the waste-to-energy process by integrating it with a BPP. The integrated design was assessed thermodynamically and economically based on a 35-MW BPP and a 500 ton/day waste-to-energy plant. The results showed that the waste-to-electricity efficiency improved from 20.49% to 22.12%, and the dynamic payback period was reduced by 2.81 years.

3. MATERIAL AND METHOD

A 1.76-MWe direct-fired BPP already operating in Adana, Turkiye is considered in this study. The plant was established in 2014 based on a steam cycle. It meets a portion of the factory's energy needs by converting cotton, corn, and soybean stalks, as well as citrus and forest residues into energy. The thermal efficiency of the BPP is an indicator based only on the amount of heat input and the work output; however, it does not reflect the ability of the system to convert energy from heat sources to useful work. Therefore, system performance cannot be evaluated based on only energy analysis; rather an exergy analysis must be considered to have the measure of irreversibility in the system that is the source of performance loss.

Firstly, the monitored data during the plant operations were collected for analysis. Secondly, mass inputs and outputs for the plant components were balanced. Thirdly, energy and exergy balances were applied for the thermodynamic analysis of each plant component. All these equations were coded in commercial software Engineering Equation Solver (EES, 2025) which is a powerful tool primarily used for solving mathematical equations related to engineering and thermodynamics. Finally, the results obtained are presented for interpretation and system improvement.

3.1. Operation of The Plant

A schematic diagram of the BPP with all associated flow is shown in Fig. 2.1. The direct-fired BPP operates through an integrated system where each component plays a crucial role in converting biomass into electricity efficiently. Biomass fuel is fed into the grate boiler which ensures proper combustion by allowing air to circulate and burning the fuel efficiently. Primary air supplied below supports combustion, while secondary air supplied above ensures the complete burning of volatile gases. The burning biomass generates hot flue gases, which move through the boiler to heat water.

The deaerator removes dissolved oxygen and gases from the feedwater, preventing corrosion in the system. The deaerated water is then preheated using waste heat in the primary economizer. Water enters the boiler drum, where it is distributed to the evaporator tubes. The hot flue gases heat the water in the evaporator, converting it into steam. The steam rises and returns to the steam drum, where it is separated from the water. The dry steam is sent respectively to the primary and secondary heaters, where it is heated further to increase energy efficiency. A steam line from the secondary heater is branched into the deaerator to heat the water further before entering the primary economizer. The high-energy steam enters the turbine, where it expands and drives the turbine blades to generate mechanical power. The turbine drives an electric generator, which produces electricity. Before flue gases exit, they pass through the primary economizer, where they transfer heat to the incoming deaerated feedwater. The recuperator is used to preheat combustion air with remaining waste heat. This component reduces fuel consumption by recovering and reusing heat. Flue gases from the boiler contain fine ash and particulates. The gases pass through the electrostatic precipitator (ESP), where charged plates attract and remove ash particles. This significantly reduces particulate emissions before releasing the cleaned gases through the chimney. After exiting the turbine, the steam is cooled in the condenser integrated into air-cooled condensers (ACCs), converting it back into water. A condensate trap is used to manage and direct condensate water formed before entering the deaerator pump.

Hot water coming from the condenser is pumped into the ACCs where it is spread over a large surface area through nozzles to maximize contact between the water and the air inside the ACCs. A small portion of the hot water evaporates and cools down the remaining water. Ambient air is drawn by fans into the ACCs that are arranged in parallel rows. The air moves through the water, absorbing the heat from the water during evaporation. The cooled water is collected in a reservoir at the base and then is pumped back into the condenser to absorb more heat. The warm, moist air that has absorbed heat from the water is then vented out of the ACCs. The lost water is fed back to the reservoir. Lastly, the condensed water in the closed cycle is pumped back into the deaerator and then the boiler drum by feedwater pumps to restart the cycle.

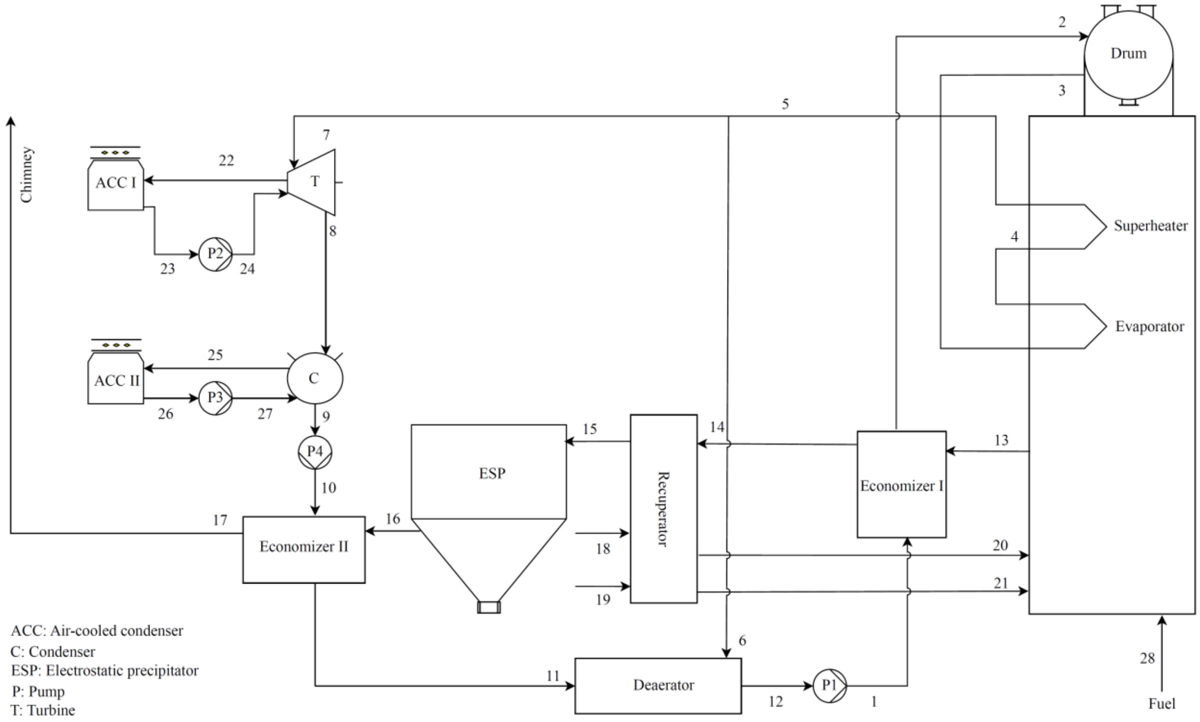

Fig. 2.1. The schematic of the plant.

3.2. Thermodynamic Relations

Thermodynamic balances for a flow process in a system during a finite time interval are needed to analyze system components (Abusoglu and Kanoglu, 2009a; Abusoglu and Kanoglu, 2009b; Kanoglu et al., 2011). The following assumptions are considered:

- The BPP operates in a steady-state condition.
- The ideal gas principles are applied to air and exhaust gases.
- The combustion reaction in the boiler is complete.
- The kinetic and potential energy changes are negligible.
- The temperature and pressure of the dead state are taken as 25 °C and 100 kPa, respectively.
- The lower heating value (LHV) of the fuel is used since the state of water in the exhaust is generally vapor.
- The system components are insulated.

With the above assumptions, mass, energy, and exergy balances for any steady-state system can be written as

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{3.1}$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{3.2}$$

$$\dot{X}_{heat} + \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \underbrace{T_0 \dot{S}_{gen}}_{\dot{X}_{dest}} \tag{3.3}$$

where $\dot{Q}$ and $\dot{W}$ are the net heat and work inputs, $\dot{m}$ is the mass flow rate of the fluid stream, h is the enthalpy, the subscripts i and e stand for inlet and exit, $T_0\dot{S}_{gen}$ is the rate of exergy destruction, and $\dot{X}_{heat}$ is the net exergy transfer by heat at temperature T, which is given by

$$\dot{X}_{heat} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q} \tag{3.4}$$

where T is the temperature at which heat transfer takes place. The specific flow exergy and the rate of total exergy are given by

$$\psi = h - h_0 - T_0(s - s_0) \tag{3.5}$$

$$\dot{X} = \dot{m}\psi \tag{3.6}$$

where the subscript 0 stands for the restricted dead state and T_0 is the dead state temperature. The energy and exergy efficiencies are generally defined as:

$$\eta = \frac{\text{energy in products}}{\text{total energy input}} \tag{3.7}$$

$$\varepsilon = \frac{\text{exergy in products}}{\text{total exergy input}} \tag{3.8}$$

The expressions of energy and exergy efficiencies for any principal types of processes are based on the above definitions. Thermodynamic analysis of a power system usually includes the assessment of individual performances of system components. In BPP systems, turbines, pumps, and HEXs are the components used.

The isentropic efficiency of a steam turbine quantifies how close the actual performance of the turbine is to the ideal isentropic process. The isentropic efficiency of an adiabatic turbine can be expressed as

$$\eta_{turb} = \frac{h_i - h_e}{h_i - h_{e,s}} \tag{3.9}$$

where the subscript s stands for the isentropic state. The second-law efficiency of an adiabatic turbine can be defined as a measure of how well the stream exergy of the fluid is converted into shaft-work output:

$$\varepsilon_{turb} = \frac{h_i - h_e}{h_i - h_e - T_0(s_i - s_e)} \tag{3.10}$$

The second-law efficiency of the HEXs in the power plant is measured by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream

$$\varepsilon_{hex} = \frac{\dot{m}_{cold}[h_i - h_e - T_0(s_i - s_e)]_{cold}}{\dot{m}_{hot}[h_i - h_e - T_0(s_i - s_e)]_{hot}} \tag{3.11}$$

For the BPP analyzed in this study, thermal efficiency is expressed as the ratio of net mechanical power to the fuel energy input:

$$\eta_t = \frac{\dot{W}}{\dot{m}_f LHV} \tag{3.12}$$

where $\dot{W} = \dot{W}_e/\eta_g$ corresponds to the net mechanical power produced by the turbine, $\dot{W}_e$ is the electric power generated by the generator, η_g is the generator efficiency. $\dot{m}_f$ is the rate of fuel input to the boiler, and LHV is the net calorific value of the fuel.

3.3. Energy and Exergy Relations

Pump-I

$$\dot{m}_{12} = \dot{m}_1 \tag{3.13}$$

$$\dot{W}_{pump-I} = \dot{m}_{12} v_{12}(P_1 - P_{12}) \tag{3.14}$$

$$e_1 - e_0 = (h_1 - h_{0,water}) - T_0(s_1 - s_{0,water}) \tag{3.15}$$

$$e_{12} - e_0 = (h_{12} - h_{0,water}) - T_0(s_{12} - s_{0,water}) \tag{3.16}$$

$$\dot{E}_{pump,I} = \dot{m}_{12}(e_1 - e_{12}) \tag{3.17}$$

$$\varepsilon_{pump-I} = \frac{\dot{E}_{pump-I}}{\dot{W}_{pump-I}} \tag{3.18}$$

$$\dot{X}_{pump-I,dest} = \dot{W}_{pump-I} - \dot{E}_{pump,I} \tag{3.19}$$

Economizer-I

$$\dot{m}_1 = \dot{m}_2 \tag{3.20}$$

$$\dot{m}_{13} = \dot{m}_{14} \tag{3.21}$$

$$\dot{Q}_{Economizer-I,actual} = \dot{m}_{13}(h_{13} - h_{14}) \tag{3.22}$$

$$e_2 - e_0 = (h_2 - h_{0,water}) - T_0(s_2 - s_{0,water}) \tag{3.23}$$

$$e_{13} - e_0 = (h_{13} - h_{0,air}) - T_0(s_{13} - s_{0,air}) \tag{3.24}$$

$$e_{14} - e_0 = (h_{14} - h_{0,air}) - T_0(s_{14} - s_{0,air}) \tag{3.25}$$

$$\varepsilon_{Economizer-I} = \frac{\dot{m}_1(e_2 - e_1)}{\dot{m}_{13}(e_{13} - e_{14})} \tag{3.26}$$

$$\dot{X}_{Economizer-I,dest} = \dot{m}_1 e_1 + \dot{m}_{13} e_{13} - \dot{m}_2 e_2 - \dot{m}_{14} e_{14} \quad (3.27)$$

<u>Drum:</u>

$$\dot{Q}_{Drum,actual} = \dot{m}_3 h_3 - \dot{m}_2 h_2 \quad (3.28)$$

$$\dot{X}_{Drum-I,dest} = \dot{m}_3 (e_3 - e_2) \quad (3.29)$$

<u>Superheater:</u>

$$\dot{m}_3 = \dot{m}_4 \quad (3.30)$$

$$\dot{Q}_{Superheater,actual} = \dot{m}_4 (h_4 - h_5) \quad (3.31)$$

$$\dot{X}_{Superheater,dest} = \dot{m}_4 (e_4 - e_5) \quad (3.32)$$

<u>Turbine:</u>

$$\dot{m}_7 = \dot{m}_8 \quad (3.33)$$

$$\dot{W}_{turbine,actual} = \dot{m}_7 (h_7 - h_8) \quad (3.34)$$

$$\dot{W}_{turbine,isentropic} = \dot{m}_7 (h_7 - h_{8s}) \quad (3.35)$$

$$\eta_{turbine} = \frac{\dot{W}_{turbine,actual}}{\dot{W}_{turbine,isentropic}} \quad (3.36)$$

$$e_7 - e_0 = (7 - h_{0,steam}) - T_0 (s_7 - s_{0,steam}) \quad (3.37)$$

$$e_8 - e_0 = (h_8 - h_{0,steam}) - T_0 (s_8 - s_{0,steam}) \quad (3.38)$$

$$\dot{E}_{turbine} = \dot{m}_7 (e_7 - e_8) \quad (3.39)$$

$$\varepsilon_{turbine} = \frac{\dot{W}_{turbine,actual}}{\dot{E}_{turbine}} \quad (3.40)$$

$$\dot{X}_{turbine,dest} = \dot{W}_{turbine,isentropic} - \dot{W}_{turbine,actual} \quad (3.41)$$

Condenser:

$$\dot{Q}_{Condenser,actual} = \dot{m}_8(h_8 - h_9) \quad (3.42)$$

$$\varepsilon_{condenser} = \frac{\dot{m}_{25}(h_{25} - h_{27})}{\dot{m}_8(h_8 - h_9)} \quad (3.43)$$

$$\dot{X}_{condenser,dest} = \dot{m}_8 e_8 + \dot{m}_{27} e_{27} - \dot{m}_9 e_9 - \dot{m}_{25} e_{25} \quad (3.44)$$

$$e_9 - e_0 = (h_2 - h_{0,water}) - T_0(s_9 - s_{0,water}) \quad (3.45)$$

$$e_{25} - e_0 = (h_{25} - h_{0,water}) - T_0(s_{25} - s_{0,water}) \quad (3.46)$$

$$e_{27} - e_0 = (h_{27} - h_{0,water}) - T_0(s_{27} - s_{0,water}) \quad (3.47)$$

Pump-IV:

$$\dot{m}_9 = \dot{m}_{10} \quad (3.48)$$

$$\dot{W}_{pump-IV} = \dot{m}_9 v_9 (P_9 - P_{10}) \quad (3.49)$$

$$e_9 - e_0 = (h_9 - h_{0,water}) - T_0(s_9 - s_{0,water}) \quad (3.50)$$

$$e_{10} - e_0 = (h_{10} - h_{0,water}) - T_0(s_{10} - s_{0,water}) \quad (3.51)$$

$$\dot{E}_{pump,IV} = \dot{m}_9(e_9 - e_{10}) \quad (3.52)$$

$$\varepsilon_{pump-IV} = \frac{\dot{E}_{pump-IV}}{\dot{W}_{pump-IV}} \quad (3.53)$$

$$\dot{X}_{pump-IV,dest} = \dot{W}_{pump-IV} - \dot{E}_{pump,IV} \quad (3.54)$$

Economizer-II:

$$\dot{m}_{10} = \dot{m}_{11} \quad (3.55)$$

$$\dot{m}_{16} = \dot{m}_{17} \quad (3.56)$$

$$\dot{Q}_{Economizer-II,actual} = \dot{m}_{16}(h_{16} - h_{17}) \quad (3.57)$$

$$e_{11} - e_0 = (h_{11} - h_{0,water}) - T_0(s_{11} - s_{0,water}) \quad (3.58)$$

$$e_{16} - e_0 = (h_{16} - h_{0,air}) - T_0(s_{16} - s_{0,air}) \quad (3.59)$$

$$e_{17} - e_0 = (h_{17} - h_{0,air}) - T_0(s_{17} - s_{0,air}) \quad (3.60)$$

$$\varepsilon_{Economizer-II} = \frac{\dot{m}_{10}(e_{11} - e_{10})}{\dot{m}_{16}(e_{16} - e_{17})} \quad (3.61)$$

$$\dot{X}_{Economizer-II,dest} = \dot{m}_{10}e_{10} + \dot{m}_{16}e_{16} - \dot{m}_{11}e_{11} - \dot{m}_{17}e_{17} \quad (3.62)$$

Deaerator:

$$\dot{Q}_{Deaerator,actual} = \dot{m}_{11}(h_{12} - h_{11}) \quad (3.63)$$

$$\varepsilon_{Deaerator} = \frac{\dot{m}_{12}e_{12}}{\dot{m}_6 e_6 + \dot{m}_{11}e_{11}} \quad (3.64)$$

$$e_6 - e_0 = (h_6 - h_{0,steam}) - T_0(s_6 - s_{0,steam}) \quad (3.65)$$

$$\dot{X}_{Deaerator,dest} = \dot{m}_6 e_6 + \dot{m}_{11}e_{11} - \dot{m}_{12}e_{12} \quad (3.66)$$

Recuperator:

$$\dot{m}_{14} = \dot{m}_{15} \quad (3.67)$$

$$\dot{m}_{18} = \dot{m}_{21} \quad (3.68)$$

$$\dot{m}_{19} = \dot{m}_{20} \tag{3.69}$$

$$\dot{Q}_{Recuporator,actual} = \dot{m}_{14}(h_{14} - h_{15}) \tag{3.70}$$

$$e_{15} - e_0 = (h_{15} - h_{0,air}) - T_0(s_{15} - s_{0,air}) \tag{3.71}$$

$$e_{18} - e_0 = (h_{18} - h_{0,air}) - T_0(s_{18} - s_{0,air}) \tag{3.72}$$

$$e_{19} - e_0 = (h_{19} - h_{0,air}) - T_0(s_{19} - s_{0,air}) \tag{3.73}$$

$$e_{20} - e_0 = (h_{20} - h_{0,air}) - T_0(s_{20} - s_{0,air}) \tag{3.74}$$

$$e_{21} - e_0 = (h_{21} - h_{0,air}) - T_0(s_{21} - s_{0,air}) \tag{3.75}$$

$$\varepsilon_{Recuporator} = \frac{\dot{m}_{18}(e_{21} - e_{18}) - \dot{m}_{19}(e_{20} - e_{18})}{\dot{m}_{14}(e_{14} - e_{15})} \tag{3.76}$$

$$\dot{X}_{Recuporator,dest} = \dot{m}_{14}e_{14} + \dot{m}_{18}e_{18} + \dot{m}_{19}e_{19} - \dot{m}_{15}e_{15} - \dot{m}_{20}e_{20} - \dot{m}_{21}e_{21} \tag{3.77}$$

Fuel Exergy:

$$\frac{\dot{X}_{fuel}}{q_{LHV}} = 1.065 \tag{3.78}$$

4. RESULTS AND DISCUSSION

As schematically depicted in Fig. 2.1, the BPP plant is composed of various components. Table 4.1 shows the data on temperature, pressure, and mass flow rate. EES with integrated thermodynamic property functions is used to calculate energy and exergy for a range of components. Each component’s input and product terms are determined to define the energy and exergy flows across them.

Table 4.1. Plant data and thermodynamic properties

State no	Fluid	$T(°C)$	$P(bar)$	$\dot{m}(ton/h)$
1	Water	103	78	8.47
2	Water	147	66	8.47
3	Water	276	64	8.47
4	Steam	346	63	8.47
5	Steam	482	61.9	8.47
6	Steam	482	3.1	0.27
7	Steam	480	60.7	8.20
8	Steam	46	0.1	8.20
9	Water	45	0.1	8.20
10	Water	45	3.5	8.20
11	Water	78	2.5	8.20
12	Water	103	2	8.47
13	Flue gas	470	1	11.79
14	Flue gas	340	0.9983	11.79
15	Flue gas	240	0.965	11.79
16	Flue gas	240	0.965	11.79
17	Flue gas	145	1	11.79
18	Air	30	1	7.48
19	Air	30	1	0.81
20	Air	225	1	7.48
21	Air	175	1	0.81
22	Oil	35	3.5	15
23	Oil	30	3.45	15
24	Oil	35	3.5	15
25	Water	43.5	4	630
26	Water	36	3.5	630
27	Water	36	4	630
28	Fuel	25	1	3.5

Table 4.2 shows the fuel properties considered in the analysis. The LHV of the biomass residue corresponds to 11.23 MJ/kg due to moisture content and ash. The use of LHV in calculations is more accurately represents the usable energy that can be obtained from the fuel, given that much of the energy involved in vaporizing water in the combustion gases is not typically recovered in the chimney.

Table 4.2. Fuel properties

Analysis	Measurement (as received)	Test method
Moisture (%)	33.20	ISO 589
Ash (%)	2.37	ISO 1171
Volatile matter (%)	50.19	ISO 562
Fixed carbon (%)	14.23	ASTM D 3172
C (%)	28.89	ASTM D 5373
H (%)	3.58	ASTM D 5373
N (%)	0.76	ASTM D 5373
S (%)	0.12	ASTM D 4259
O (%)	31.05	ASTM D 3176
HHV (kcal/kg)	3074	ISO 1928
LHV (kcal/kg)	2685	ISO 1928

The generator efficiency which is taken to be ~0.98 refers to the ratio of the electrical power output of a generator to the mechanical power input required to operate it. The first-law efficiency of the BPP is calculated to be 16.5%, which is reasonable and close to those in the literature (Wang et al., 2015). The efficiency of grate-fired boilers in BPPs typically ranges from 20% to 22% for smaller plants and high-moisture fuels based on fuel characteristics, boiler design, and operational practices. Higher moisture content in biomass fuels can affect combustion efficiency, as more energy is required to evaporate the water before the fuel can fully combust. Power plants that use cotton residues often need to manage the moisture content to optimize energy production, which could involve drying or conditioning the material before combustion. Biomass combustion technologies can be less efficient compared to other forms of power generation since the energy density of biomass is lower than that of fossil fuels, which can lead to a larger volume of fuel being required and more waste to be processed.

On the other hand, the efficiency of grate-fired boilers typically ranges from 70% to 85%, depending on various factors, including the type of biomass, boiler design, and operational practices (Eswaravelu et al., 2024). It indicates how efficiently a boiler converts the energy in the fuel into steam that can be used for power generation. The boiler efficiency is calculated as 59.3% but it rises to 68.7% if the energy supply is initiated from the condenser exit. The boiler exhaust gas heats the water from the condenser outlet to the superheater outlet. The findings are comparable to the literature. The boiler efficiency is highly affected by the calorific value, moisture content of the biomass fuel, and boiler heat losses.

Table 4.3 represents the energetic and exergetic analyses results for the subsystems in the BPP. Among the components, the condenser has the highest exergy destruction which is mainly driven by the lower temperature difference relative to the dead state. Recuperator, Economizer-I and Economizer-II at exergetic efficiencies values of 41.7%, 42.0% and 29.6%, respectively which indicate similar heat transfer from exhaust gas to water. Pump-I has exergetic efficiency at 93.9% which works almost at maximum performances. On the other hand, the isentropic efficiency of the turbine is estimated to be 65% which is less than typical isentropic efficiency (between 80% and 90%) for steam turbines, but it can vary depending on factors such as age, maintenance, design, and operating conditions. It is an important metric for evaluating turbine performance, and a higher isentropic efficiency indicates a more effective conversion of steam energy into mechanical work.

Table 4.3. Energetic and exergetic results in the plant based on components

Components	$\dot{W}$ (kW)	$\dot{Q}$ (kW)	$\dot{X}_{dest}$ (kW)	ε (%)
1. Pump-I	18.7	−	1.14	93.9
2. Economizer-I	−	455.3	147.9	42.0
3. Drum	−	1395	534.7	−
4. Superheater	−	5080	2442	−
5. Turbine	1795	−	970.8	66.5
6. Condenser	−	5452	106.4	70.1
7. Economizer-II	−	318.4	80.4	29.6
8. Deaerator	−	226.2	28.5	75.2
9. Recuperator	−	341.5	99.1	41.7

The exergy destructions for each component of the system are shown in Fig. 4.1 to compare the irreversibilities generated. The fuel exergy input under the given conditions is 11632 kW of which 47% is the highest fraction destructed by the cooling water of ACC-II and followed by the superheater and turbine. The main reason is that the condenser has a low operating temperature close to the dead state. The exergy destruction from the pump can be neglected as seen. The results are comparable with the studies of (Kaşka, 2014; Ozdil et al., 2015).

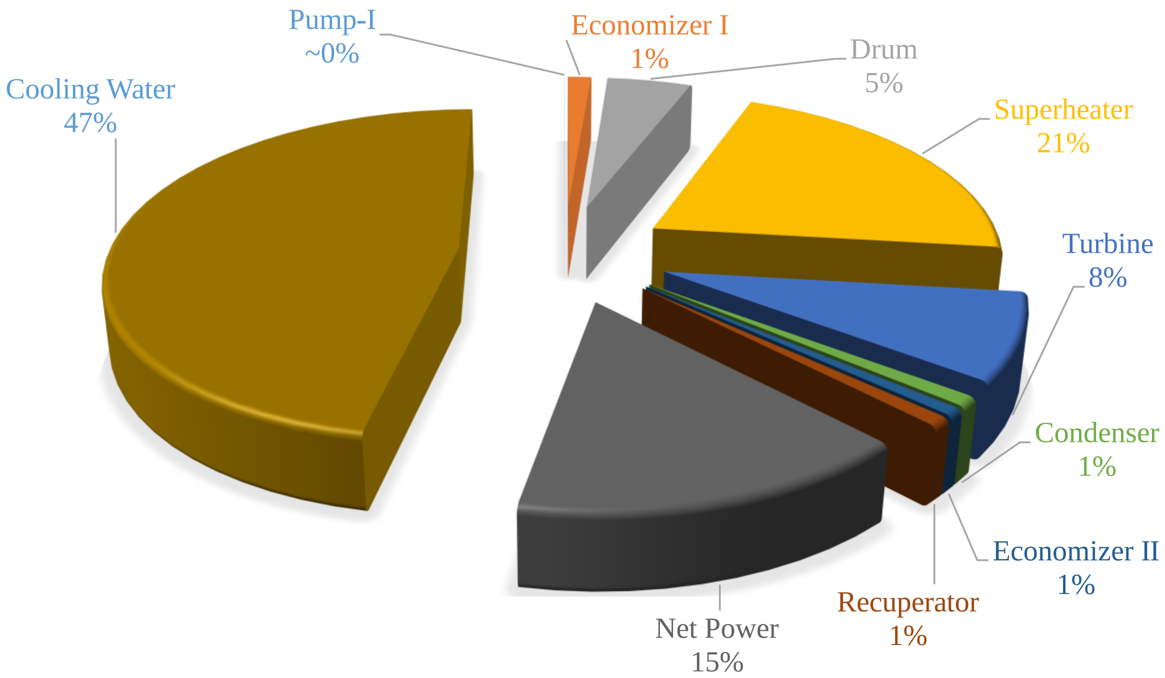

Fig. 4.1. The rate of exergy destructions of the components based on fuel exergy input.

Fig. 4.2 shows how the power, exergy destruction and the second-law efficiency of the boiler feedwater pump (Pump-I) vary with increasing inlet pressure. While second-law efficiency increases too slightly with pressure, the pumping power demand drops remarkably. This means that increasing the inlet pressure does not influence second-law efficiency, but it lowers the pumping power consumption and exergy destruction. It is not an effective parameter on thermal efficiency, but plant design should consider what the pumping inlet pressure would be more feasible for energetic efficiency.

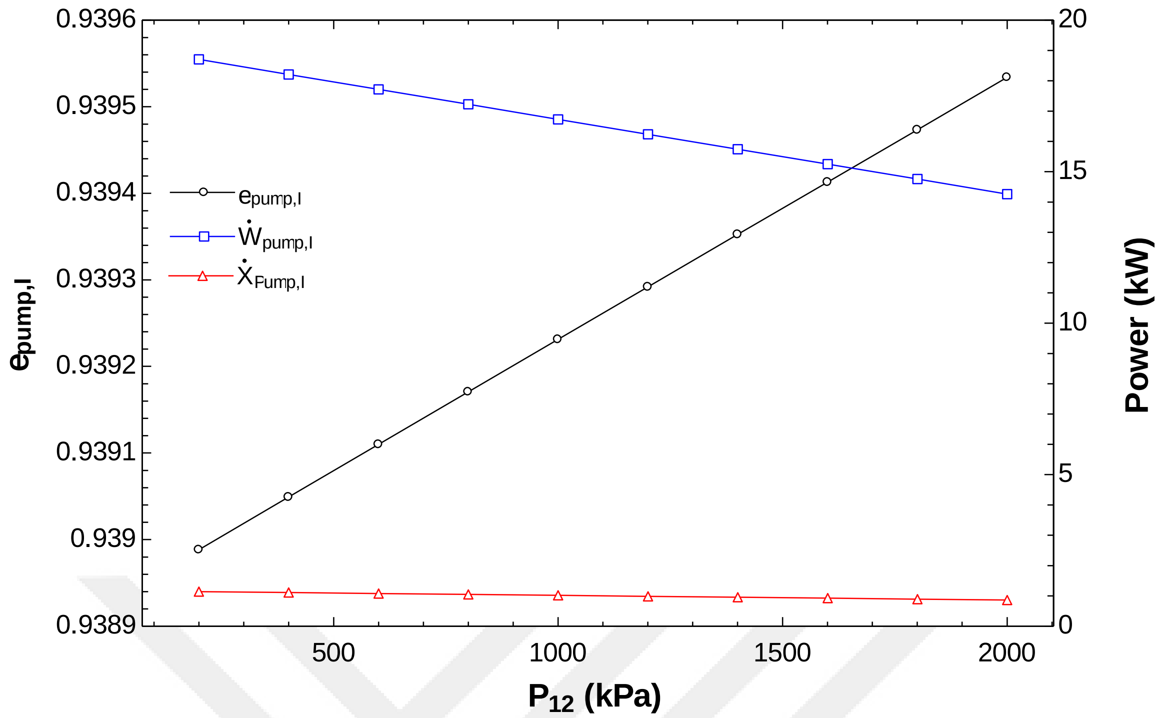

Fig. 4.2. Variation of performance parameters for Pump-I with inlet pressure.

Fig. 4.3 shows the variation of the power, exergy destruction, and second-law efficiency of Economizer-I with increasing inlet temperature. The heat capacity of Economizer-I increases with temperature along with increasing efficiency. As the capacity has nearly quadrupled, the second-law efficiency increases by 22%. As seen, the slope of the thermal power line is higher than that of the exergy destruction line. This means that increasing temperature lowers the exergy destruction in the component as expected.

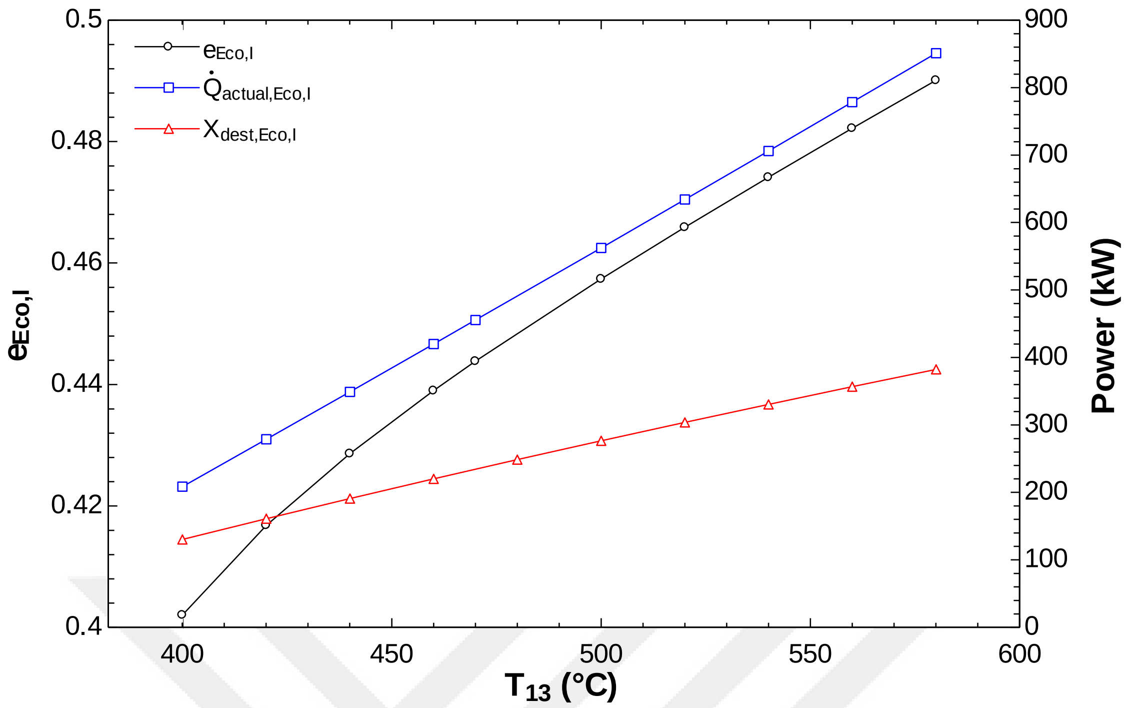

Fig. 4.3. Variation of performance parameters for Economizer-I with inlet temperature.

Fig. 4.4 demonstrates the variation of the turbine inlet temperature on the isentropic and second-law efficiencies of the turbine as the turbine outlet state is kept the same. The isentropic efficiency decreases 11.5% if the output mechanical power is the same. To increase the isentropic turbine efficiency, the more reasonable comparison will be the change of actual power with increasing turbine inlet temperature. This change is clearly seen in the second-law efficiency curve which increases 16% per 90 °C temperature increase.

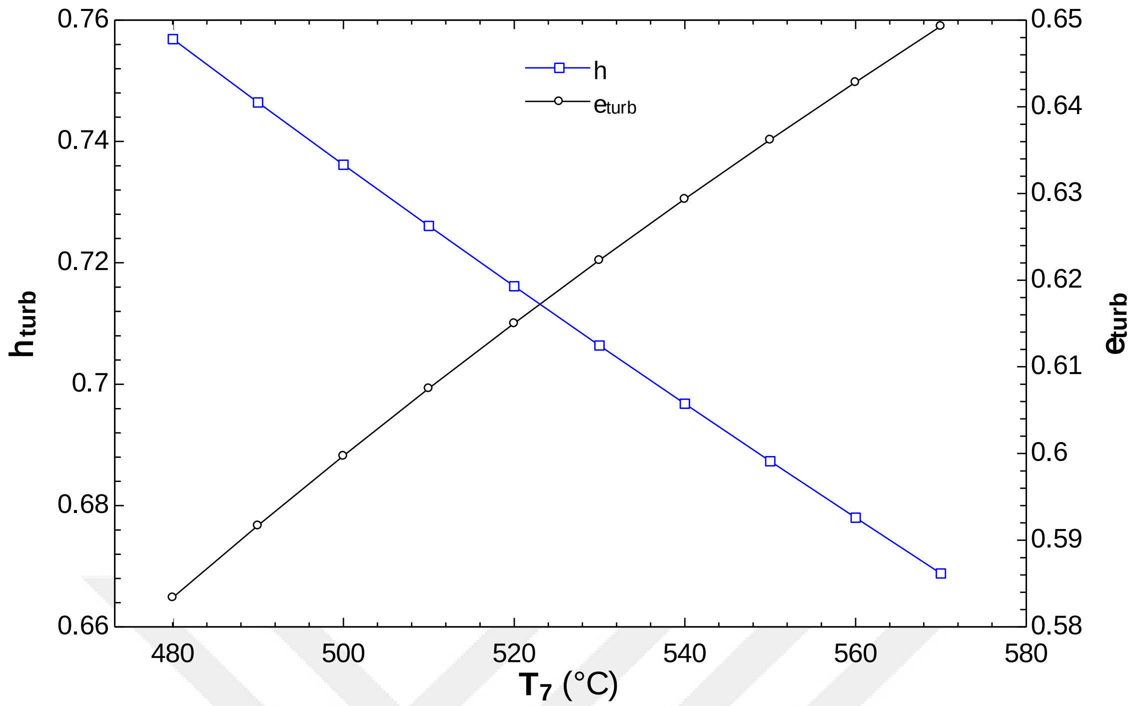

Fig. 4.4. Variation of the efficiencies with turbine inlet temperature.

Fig. 4.5 shows the effect of the condenser inlet temperature on the variation of thermal capacity, exergy destruction and second-law efficiency of the condenser for the same condenser outlet. Increasing condenser inlet temperature has a slight but positive effect on the condenser capacity as expected. The energetic capacity of the condenser is very high, but the exergy input is almost fully destructed from this component due to low reservoir temperature. The second-law efficiency lowers but the change is less than 0.4%.

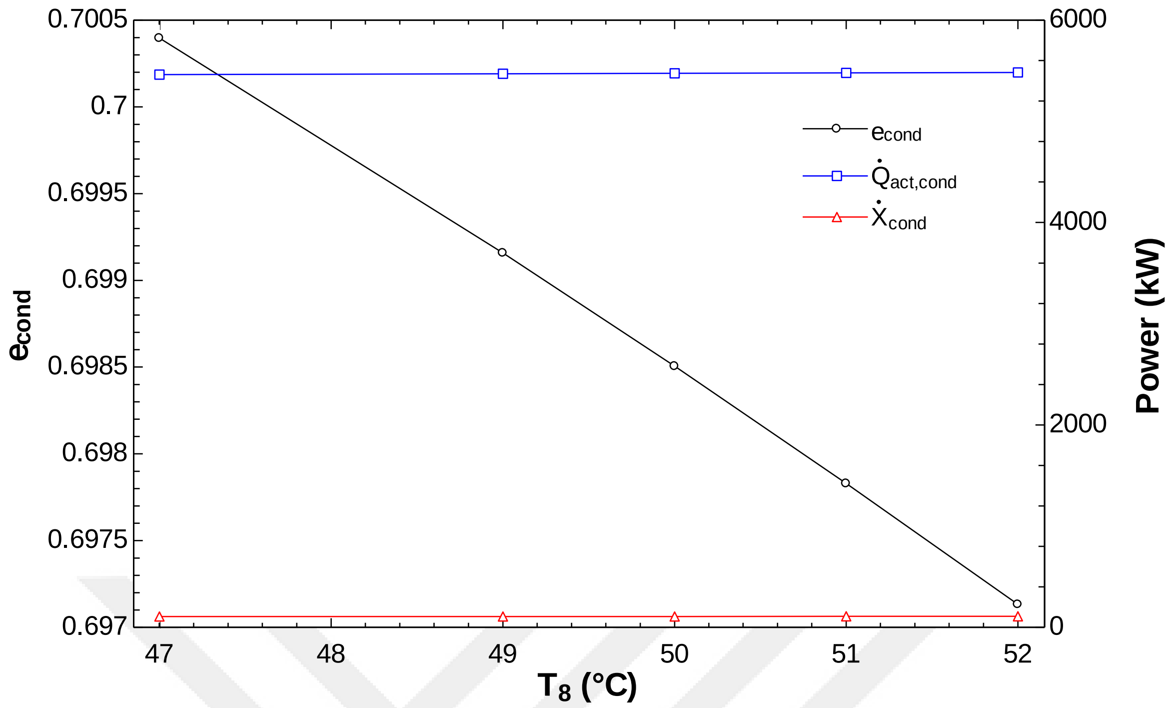

Fig. 4.5. Variation of the properties for the condenser with inlet temperature.

Fig. 4.6 demonstrates the variation of the recuperator inlet temperature on the exergy destruction and second-law efficiency of the recuperator. Increasing inlet temperature by keeping the device capacity constant drops the efficiency although its exergy destruction lowers with increased temperature. This means that lowering the inlet temperature will improve the recuperator efficiency and the plant operators need to consider this point for better exergy flow. ~90 °C increase in the inlet temperature lowers the efficiency 15%.

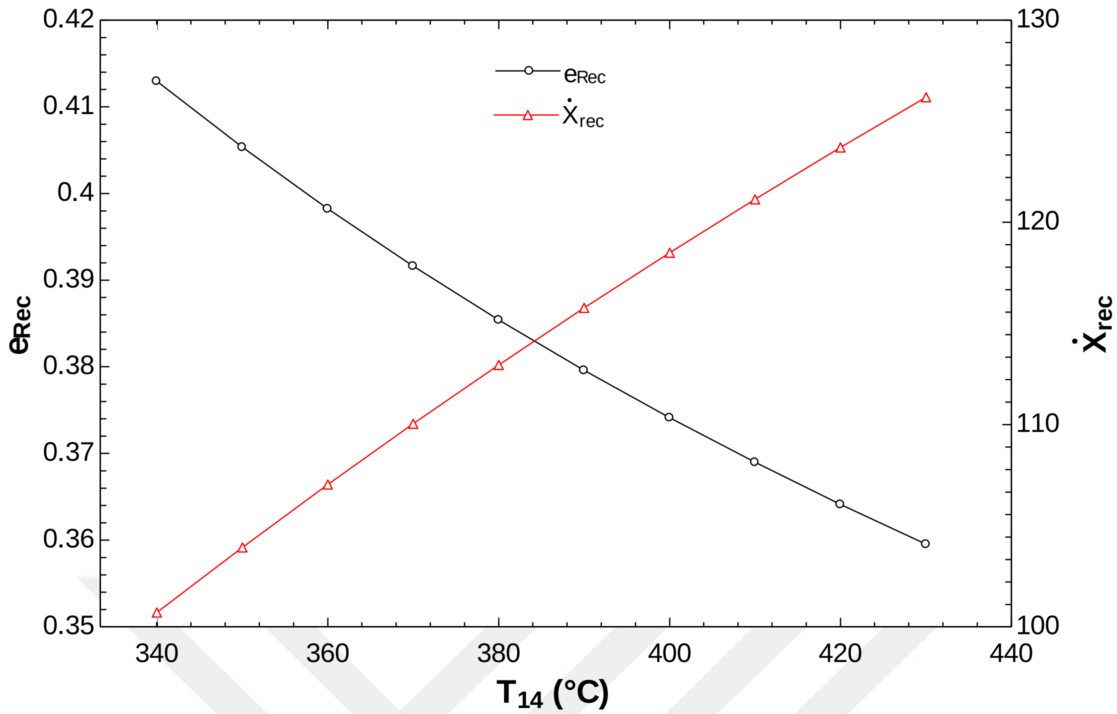

Fig. 4.6. Variation of the efficiency and exergy destruction of the recuperator.

Fig. 4.7 shows how the water inlet temperature affects the exergy destruction and second-law efficiency of the deaerator while other parameters are kept constant. Both the efficiency and exergy destruction decrease with increasing water temperature. The steam injected into the deaerator is usually at a high temperature and pressure, and it undergoes an expansion when it mixes with the feedwater. This expansion process is irreversible and generates entropy because of the non-ideal mixing of steam and water.

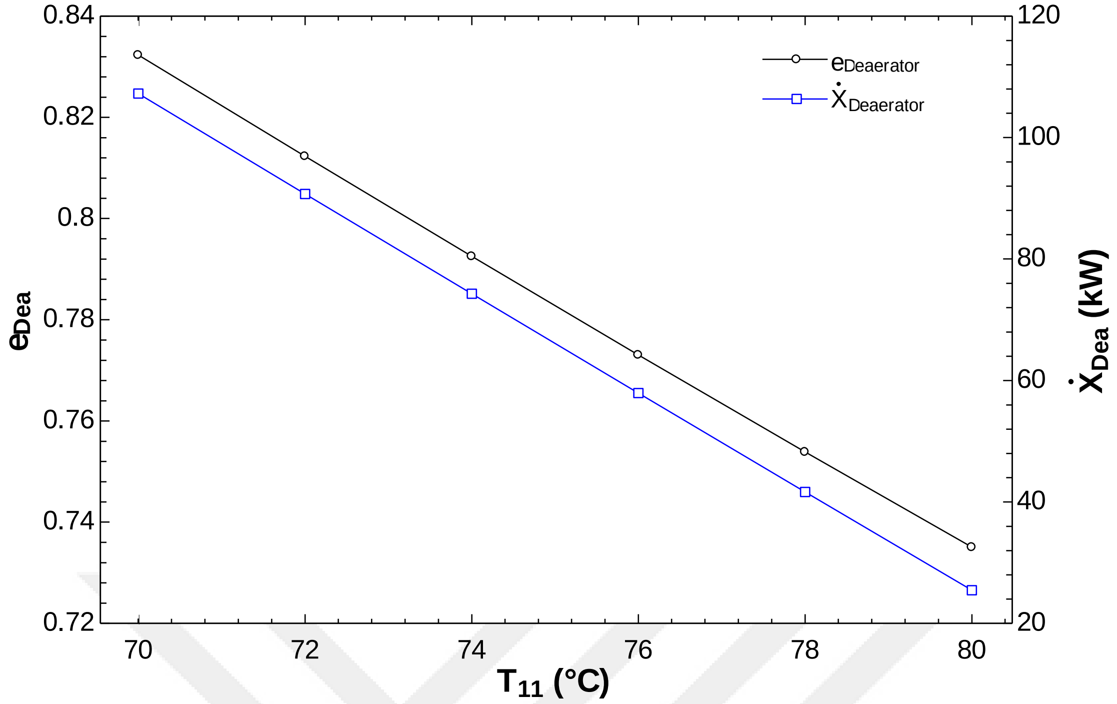

Fig. 4.7. Variation of the efficiency and exergy destruction of the deaerator.

5. CONCLUSION

In conclusion, the energy and exergy analysis of a direct-fired BPP provides valuable insights into its overall performance, highlighting areas for potential efficiency improvement. Energy analysis helps quantify the amount of energy input and output, revealing the effectiveness of energy conversion in the system. However, exergy analysis offers a deeper understanding by evaluating the quality of energy flows, identifying losses due to irreversibilities in the system, and pinpointing inefficiencies that may not be visible through energy analysis alone.

The results from both analyses typically show that the BPP experiences substantial energy losses, mainly due to high temperature irreversibilities, suboptimal combustion processes, and heat losses from the boiler and HEXs. These losses reduce the overall efficiency of the plant, making it less effective in converting the biomass fuel into useful work.

To improve efficiency, several strategies can be considered. These include optimizing the combustion process to ensure more complete fuel utilization, enhancing heat recovery systems, and implementing better turbine and generator technologies. Additionally, integrating CHP systems could significantly improve both the thermal and electrical efficiencies of the plant. Moreover, adopting advanced control systems, incorporating waste heat recovery, and exploring hybridization with other renewable energy sources could further reduce exergy losses and improve overall system performance.

By addressing these inefficiencies, a direct-fired BPP's overall efficiency and sustainability can be greatly enhanced, contributing to more cost-effective and environmentally-friendly energy production from biomass resources.

- The first-law efficiency of the BPP is calculated to be 16.5%, which is reasonable and close to those in the literature.
- The boiler efficiency is calculated as 59.3% but it rises to 68.7% if the energy supply is initiated from the condenser exit.
- Recuperator, Economizer-I and Economizer-II at exergetic efficiencies values of 41.7%, 42.0% and 29.6%, respectively.

- The fuel exergy input under the given conditions is 11632 kW of which 47% is the highest fraction destructed by the cooling water of ACC-II and followed by the superheater and turbine.
- The isentropic efficiency of the turbine is estimated to be 65% which is less than typical isentropic efficiency (between 80% and 90%) for steam turbines, but it can vary depending on factors such as age, maintenance, design, and operating conditions.
- The condenser is the primary source of exergy destruction, and efforts should focus on improving its efficiency.
- Optimizing inlet pressures and temperatures in pumps, recuperators, and economizers can enhance system performance.
- Higher turbine inlet temperatures benefit second-law efficiency, but trade-offs exist for isentropic efficiency.
- Lower recuperator inlet temperatures significantly improve efficiency, making it a key design consideration.
- System design should carefully balance exergy destruction minimization with efficiency improvements across components.

REFERENCES

Abusoglu, A., & Kanoglu, M. (2009a). Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1–Formulations. Applied Thermal Engineering, 29(2-3), 234-241.

Abusoglu, A., & Kanoglu, M. (2009b). Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 2–Application. Applied Thermal Engineering, 29(2-3), 242-249.

Al Asfar, J., AlShwawra, A., Shaban, N. A., Alrbai, M., Qawasmeh, B. R., Sakhrieh, A., ... & Odeh, O. (2020). Thermodynamic analysis of a biomass-fired lab-scale power plant. Energy, 194, 116843.

Al-Sulaiman, F. A., Dincer, I., & Hamdullahpur, F. (2012). Energy and exergy analyses of a biomass trigeneration system using an organic Rankine cycle. Energy, 45(1), 975-985.

Azami, S., Taheri, M., Pourali, O., & Torabi, F. (2018). Energy and exergy analyses of a mass-fired boiler for a proposed waste-to-energy power plant in Tehran. Applied Thermal Engineering, 140, 520-530.

Bilgili, M. E. (2020). Usage of agricultural biomass potential in electricity substitution in Adana province. Osmaniye Korkut Ata University Journal of Natural and Applied Sciences, 3(1), 41-47.

Bilgili, M. E. (2022). Exploitable potential of biomass energy in electrical energy production in the Mediterranean Region of Turkey. Journal of Agricultural Sciences, 28(4), 666-676.

Braimakis, K., Magiri-Skouloudi, D., Grimekis, D., & Karellas, S. (2020). Energy-exergy analysis of ultra-supercritical biomass-fuelled steam power plants for industrial CHP, district heating and cooling. Renewable Energy, 154, 252-269.

Caliskan, M., & Tumen Ozdil, N. F. (2021). Potential of biogas and electricity production from animal waste in Turkey. BioEnergy Research, 14(3), 860-869.

Can, M. E. (2021). Büyükbaş hayvan ve tavuk gübreleri kaynaklı biyogaz potansiyeli; Adana ili örneği. Mediterranean Agricultural Sciences, 34(2), 205-214.

Cavalcanti, E. J., Carvalho, M., & Azevedo, J. L. (2019). Exergoenvironmental results of a eucalyptus biomass-fired power plant. Energy, 189, 116188.

Channiwala, S. A., & Parikh, P. P. (2002). A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel, 81(8), 1051-1063.

Costa, V. A. F., Tarelho, L. A. C., & Sobrinho, A. (2019). Mass, energy and exergy analysis of a biomass boiler: A portuguese representative case of the pulp and paper industry. Applied Thermal Engineering, 152, 350-361.

Dağtekin, M., Aybek, A., & Bilgili, M. E. (2019). Adana ve Mersin'de bulunan etlik piliç kümeslerinde oluşan gübrenin biyogaz ve elektrik üretim potansiyelinin belirlenmesi. Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 34(2), 9-22.

Datta, A., Ganguly, R., & Sarkar, L. (2010). Energy and exergy analyses of an externally fired gas turbine (EFGT) cycle integrated with biomass gasifier for distributed power generation. Energy, 35(1), 341-350.

Demir, K. (2019). Adana ilinde sıfır atık projesinin uygulanması (Master's thesis, Nevşehir Hacı Bektaşi Veli Üniversitesi Fen Bilimleri Enstitüsü).

Demirbas, A. (2008). Importance of biomass energy sources for Turkey. Energy Policy, 36(2), 834-842.

Eboh, F. C., Ahlström, P., & Richards, T. (2017). Exergy analysis of solid fuel-fired heat and power plants: a review. Energies, 10(2), 165.

EES, Engineering Equation Solver. https://fchartsoftware.com/ees/. Accessed on Jan 25, 2025.

Enerji Atlası: Biyogaz, Biyokütle, Atık Isı ve Pirolitik Yağ Enerji Santralleri. https://www.enerjiatlasi.com/biyogaz/. Accessed on Jan 25, 2025.

Eswaravelu, D., Narayanasamy, M., Mohan, U., & Narayanagounder, S. (2024). Thermodynamic Analysis of Grate Fired Boiler Efficiency using Biomass Fuels. In 1st International Conference on Innovative Engineering Sciences and Technological Research (ICIESTR) (pp. 1-5). IEEE.

Kanoglu, M., Ayanoglu, A., & Abusoglu, A. (2011). Exergoeconomic assessment of a geothermal assisted high temperature steam electrolysis system. Energy, 36(7), 4422-4433.

Kaşka, Ö. (2014). Energy and exergy analysis of an organic Rankine for power generation from waste heat recovery in steel industry. Energy Conversion and Management, 77, 108-117.

Kaushik, S. C., Reddy, V. S., & Tyagi, S. K. (2011). Energy and exergy analyses of thermal power plants: A review. Renewable and Sustainable Energy Reviews, 15(4), 1857-1872.

Li, C., Gillum, C., Toupin, K., & Donaldson, B. (2015). Biomass boiler energy conversion system analysis with the aid of exergy-based methods. Energy Conversion and Management, 103, 665-673.

Mallaki, M., & Fatehi, R. (2014). Design of a biomass power plant for burning date palm waste to cogenerate electricity and distilled water. Renewable Energy, 63, 286-291.

Manić, N., Janković, B., Milović, L., Komatina, M., & Stojiljković, D. (2021). The impact of production operating parameters on mechanical and thermophysical characteristics of commercial wood pellets. Biomass Conversion and Biorefinery, 1-17.

Mehmood, S., Reddy, B. V., & Rosen, M. A. (2015). Exergy analysis of a biomass co-firing based pulverized coal power generation system. International Journal of Green Energy, 12(5), 461-478.

Mimsan. https://www.mimsanenergy.com/urunler/biyokutle-yakitli-enerji-santralleri/. Accessed on Jan 25, 2025.

Ozdil, N. F. T., Segmen, M. R., & Tantekin, A. (2015). Thermodynamic analysis of an Organic Rankine Cycle (ORC) based on industrial data. Applied Thermal Engineering, 91, 43-52.

Ozdil, N. F. T., & Tantekin, A. (2016). Exergy and exergoeconomic assessments of an electricity production system in a running wastewater treatment plant. Renewable Energy, 97, 390-398.

Ozdil, N. T., & Caliskan, M. (2022). Energy potential from biomass from agricultural crops: Development prospects of the Turkish bioeconomy. Energy, 249, 123770.

Pan, P., Zhang, M., Xu, G., Chen, H., Song, X., & Liu, T. (2020). Thermodynamic and economic analyses of a new waste-to-energy system incorporated with a biomass-fired power plant. Energies, 13(17), 4345.

Pesen, D., Gençay, G., & Kurşun, B. (2023). Environmental and economic analysis of bioenergy production and utilization in Adana Turkey. Celal Bayar University Journal of Science, 19(1), 1-10.

Saidur, R., BoroumandJazi, G., Mekhilef, S., & Mohammed, H. A. (2012). A review on exergy analysis of biomass based fuels. Renewable and Sustainable Energy Reviews, 16(2), 1217-1222.

Saka, K., & Yılmaz, İ. H. (2017). Agricultural biomass potential in Turkey. International Journal of Management and Applied Science, 3(2), 79-81.

Saka, K., Yılmaz, İ. H., Canbolat, A. S., & Kaynaklı, Ö. (2018). Energy potential of animal biomass in Turkey. European Journal of Technique, 8(2), 160-167.

Sikarwar, S. S., Surywanshi, G. D., Patnaikuni, V. S., Kakunuri, M., & Vooradi, R. (2020). Chemical looping combustion integrated Organic Rankine Cycled biomass-fired power plant–Energy and exergy analyses. Renewable Energy, 155, 931-949.

Silva, J., Teixeira, S. F., Preziati, S., & Teixeira, J. C. (2016). Energy and exergy analysis of a biomass power plant. In ASME International Mechanical Engineering Congress and Exposition (Vol. 50596, p. V06BT08A026).

Soltani, S., Yari, M., Mahmoudi, S. M. S., Morosuk, T., & Rosen, M. A. (2013). Advanced exergy analysis applied to an externally-fired combined-cycle power plant integrated with a biomass gasification unit. Energy, 59, 775-780.

Tanrıverdi, E. A. (2022). Adana ilinin tarımsal atık kaynaklı biyokütle potansiyelinin araştırılması (Master’s thesis, Adana Alparslan Türkeş Bilim ve Teknoloji Üniversitesi Sosyal Bilimler Enstitüsü).

Wang, C., Zhang, L., Chang, Y., & Pang, M. (2015). Biomass direct-fired power generation system in China: An integrated energy, GHG emissions, and economic evaluation for Salix. Energy Policy, 84, 155-165.

Yan, L., Wang, Z., Cao, Y., & He, B. (2020). Comparative evaluation of two biomass direct-fired power plants with carbon capture and sequestration. Renewable Energy, 147, 1188-1198.

Yılmaz, İ. H., & Saka, K. (2018). Exploitable biomass status and potential of the Southeastern Anatolia Region, Turkey. Energy Sources, Part B: Economics, Planning, and Policy, 13(1), 46-52.

Yılmaz, İ. H., & Abdulvahitoğlu, A. (2019). Evaluation of municipal solid waste options in Turkey: Scenarios for energy recovery, carbon mitigation and consequent financial strategies. Resources, Conservation and Recycling, 147, 95-110.

Yılmaz, İ. H. (2022). Quantification and characterization of cotton residues as fuel: The case of Cukurova. In 8th Virtual International Conference on Science, Technology and Management in Energy (eNergetics 2022), 39-42.